Phase Diagram and Spectroscopy of Fulde-Ferrell-Larkin-Ovchinnikov States of Two-Dimensional d-wave Superconductors

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Experimental evidence is growing that the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state may be realized in the unconventional, heavy-fermion superconductor $CeCoIn_5$ [1, 2]. If confirmed, this would be the first identified system undergoing a phase transition from the uniform Meissner state of the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity to the spatially nonuniform FFLO state. To provide further tests for its identification we calculated the magnetic field versus temperature phase diagram. This involves a self-consistent calculation of the superconducting order parameter structures for the FFLO states of quasi-two-dimensional d-wave superconductors. Our results predict that the lower critical magnetic field transition between the spatially uniform Meissner and nonuniform FFLO state is of second order, signaled by the appearance of a single domain wall. Thus the signatures of the nonuniform FFLO state should be clearly observable in the I-V characteristics of scanning tunneling spectroscopy measurements.

The FFLO state is predicted for clean spin-singlet superconductors as a result of the competition between pairing correlations favoring anti-parallel spin alignment and the Zeeman effect favoring parallel spin alignment along the field. The compromise is a spatially inhomogeneous state of “normal” and “superconducting” regions. The “normal” regions are defined by a spectrum of spin-polarized quasiparticles. The high-field FFLO phase was originally suggested for superconductors with ferromagnetically aligned impurities, but it was soon realized that a FFLO state should develop in superconductors in an external field if the Zeeman coupling dominates over the orbital coupling.

We performed a comprehensive stability analysis of the nonuniform FFLO phases for two-dimensional (2-D) d-wave superconductors [3]. Our analysis is for applied fields parallel to the superconducting layers over the field range from the lower critical field, B_{c1}, to the upper critical field, B_{c2}. In this geometry the effect of the magnetic field on the superconducting condensate enters only through the Zeeman coupling of the quasiparticle spin to the field. For simplicity we assumed a cylindrical Fermi surface, which is also supported by de Haas-van Alphen measurements on $CeCoIn_5$.

By solving the Eilenberger equation in a magnetic field **B** for the quasiclassical Green’s functions, we obtained information about the local density of states and the free energy density [3]. From the latter one we constructed the phase diagram shown in Fig. 1. The Larkin-Ovchinnikov (LO) state is stabilized in the high-**B**, low-T region of the phase diagram. The solid lines in Fig. 1 are second-order phase transition lines that determine the upper critical field, B_{c2}, and separate the normal and FFLO states below the critical point $T_{FFLO} = 0.56\ T_c$. Below $T \sim 0.06\ T_c$ a first-order transition (long-dashed line) occurs between order parameter modulations along [110] and [100] directions. At the lower critical field, B_{c1} a second-order transition (circles-solid) occurs between the uniform and nonuniform [110] oriented LO phase. The unphysical transition line from the uniform state into the [100] oriented nonuniform state is shown for comparison (short-dashed). The Chandrasekhar-Clogston phase transition line between the uniform superconducting and normal state would be of first order below T_{FFLO} (dot-dashed), but is unphysical. However, it is of second order and physical above T_{FFLO} (thick dot-dashed).

The spin-polarized local quasiparticle density of states (LDOS) is very sensitive to domain walls, where the superconducting order parameter changes sign. In Fig. 2 we show the evolution of the LDOS for spin-up and spin-down excitations for $T/T_c = 0.15$ and $b = \mu B/2\pi T_c = 0.175$ at the domain wall [position (a)] and far away from it [position (b)]. The spin-down (spin-up) LDOS are shown as solid (dashed) lines. Two distinct Andreev bound states, split by $\Delta\varepsilon/2\pi T_c = 2b$, are seen in the middle panel. Once one moves far away from the domain wall [position (b)], see bottom panel, the Andreev bound states have decayed substantially.

In conclusion, the calculated phase diagram does not resemble the experimental one. However, the LDOS calculations suggest that the Andreev resonance spectrum may be used to identify experimentally the intrinsic structure of the FFLO phases. In particular, the topological Andreev bound state is shifted from zero energy by an applied magnetic field. Also their spatial distribution depends on the wavelength of the nonuniform modulations, which are controlled by the strength of the magnetic field. Besides the characteristic energy dependence of the resonances, their spatial periodicity in the FFLO state enables us to tell them apart from random impurities in scanning tunneling spectroscopy measurements.

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[2] H. Radovan, et al., *Nature* **425**, 51 (2003).
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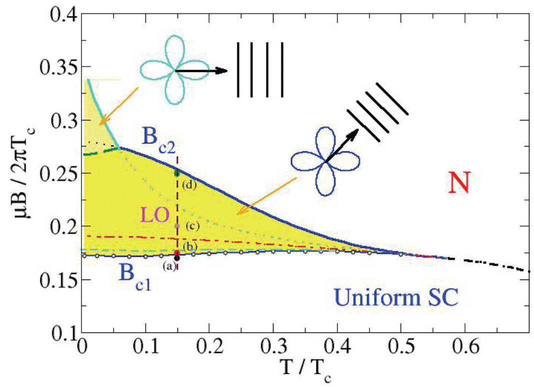

Fig. 1. ***Phase diagram of FFLO phases of a 2-D d-wave superconductor (see text for description).***

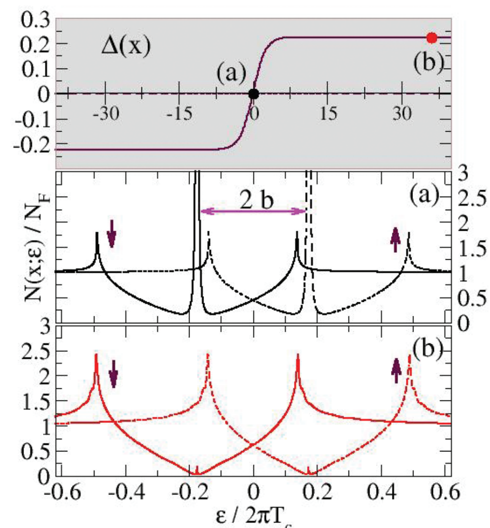

Fig. 2. ***LDOS of spin-up (spin-down) excitations near a single domain wall at positions (a) and (b).***